- Partition coefficient of an organic chemical between organic carbon and water (K_{oc}).

- Partition coefficient of an organic chemical between octanol (an organic liquid) and water (K_{ow}).

The porosity of the soil medium, the soil bulk density, f_{oc}, K_d, K_{oc}, and K_{ow} will be discussed later in this section and used to estimate the velocities of TCE and PCE in the groundwater at the Newmark site. The average groundwater velocity for the Newmark plume, which was estimated in Section 12.3, will also be used in this estimation.

13.1 Fate and Transport of TCE and PCE

The Newmark plume is composed of the chlorinated organic chemicals TCE and PCE that were detected in the groundwater in 1980 at concentrations exceeding federal and state action levels for public drinking water supplies. A thorough understanding of the mass transport and geochemical fate of TCE and PCE in the groundwater system is required to predict the rate of migration and design a remediation extraction system for the Newmark site. In this section, the term groundwater system will include the groundwater and the soil medium that exist below the water table.

The migration of TCE and PCE in groundwater system is governed by advection-dispersion processes and geochemical processes. Advection and dispersion are mass transport processes responsible for moving dissolved mass (ie. dissolved TCE and PCE) in groundwater systems. Geochemical processes govern the fate of organic chemical in the groundwater system and include chemical transformations (such as volatilization, biodegradation, oxidation, reduction, hydrolysis and photolysis) and adsorption processes (Richards and Shieh 1986). Together, advection-dispersion and geochemical processes that occur in the groundwater system determine the fate and transport of TCE and PCE in the groundwater.

The term advection describes mass transport due simply to the flow of water in which the mass is dissolved. The direction and rate of transport coincides with that of the groundwater. Dispersion is a process of fluid mixing that causes a zone of mixing to develop between a fluid of one composition that is adjacent to or being displaced by a fluid of another composition and is usually assumed to occur at a negligible rate. MODFLOW is a groundwater flow program and, therefore, is only capable of simulating the advection processes that take place in the groundwater flow system. Therefore, MODFLOW can be used to simulate the direction and, to some extent, the rate of transport of the dissolved TCE and PCE that exists in the groundwater. The dispersion characteristics of TCE and PCE in the groundwater are assumed to be negligible.

Migration of TCE and PCE in the groundwater also depends on the geochemical processes that occur in the groundwater system. Chemical transformations are first-order kinetic reactions in which the organic chemical is broken down into inorganic and other organic by-products. Volatilization and biodegradation are the chemical transformations that would most likely affect TCE and PCE in favorable conditions. Favorable conditions in the groundwater system are essential for promotion of volatilization and biodegradation of TCE and PCE. Volatilization, biodegradation and the other potential chemical transformations of TCE and PCE are discussed in more detail in Section 6.0.

Adsorption is a term used to describe the distribution of the dissolved organic chemical in the groundwater between the liquid phase (groundwater or organic liquid) and the solid matrix (soil surfaces or organic material in the soil). Three partitioning coefficients describe the potential for adsorption of the organic chemical in the groundwater system:

- Adsorption or distribution coefficient of an organic chemical between soil surfaces and water (K_d).

- Partition coefficient of an organic chemical between organic carbon and water (K_{oc}).

- Partition coefficient of an organic chemical between octanol (an organic liquid) and water (K_{ow}).

The distribution coefficient can be used to define the retardation factor which expresses the velocity of TCE and PCE migration relative to the groundwater velocity.

Furthermore, the degree of adsorption not only affects a chemical's mobility but also other transport and transformation reactions. For example, the rates of volatilization, photolysis, hydrolysis and biodegradation of many organic chemicals are directly dependent upon the extent of adsorption (Dragun, 1988).

The velocities of TCE and PCE in the groundwater tend to be affected mostly by volatilization, biodegradation and adsorption processes discussed above. However, at the Newmark site, it is assumed that volatilization and biodegradation of TCE and PCE do not occur at appreciable rates. This is probably true because most of the favorable soil conditions, which are required for these processes to occur, do not exist in the groundwater system at the Newmark site. Therefore, the velocities of TCE and PCE that will be estimated in the next sub-section will be based on the potential for adsorption.

13.2 Retardation Factors and Velocities of TCE and PCE in the Groundwater

Organic chemicals that are present in groundwater systems tend to travel at retarded velocities, compared to the groundwater velocities. The velocities for organic chemicals in the groundwater system are retarded due to the adsorption processes discussed earlier in the previous sub-section. The retardation factor (R_f) that is used to express the velocity of an organic chemical relative to the groundwater velocity is determined by the following equation:

$$R_f = V_w / V_c = 1 + \{(1 - n) / n\} \varrho_s K_d \qquad (1)$$

where V_w is the velocity of the groundwater; V_c is the velocity of the organic compound; ϱ_s is the soil particle density (assume 2.65 g/cm^3); n is the porosity of the soil medium (assume 30% for the soil medium at the Newmark site); and K_d is the adsorption or distribution coefficient (Domenico and Schwartz 1990).

The distribution coefficient, K_d, is used to express the adsorption potential (or the distribution of an organic chemical between soil surfaces and water). The simplest and most common method for mathematically expressing adsorption potential is defined as the following ratio:

$$K_d = C_s/C_w \qquad (2)$$

where C_s is the concentration adsorbed on soil surfaces (ug/g soil) and C_w is the concentration in water (ug/ml) (Dragun 1988).

If equation (2) is normalized on the basis of the soil's organic carbon content, much of the variation observed among K_d values over different soils can be eliminated. Normalized K_d values can be expressed in the following form:

$$K_d = K_{oc}\, f_{oc} \qquad (3)$$

where K_{oc} is the normalized soil adsorption coefficient or partition coefficient of an organic compound between organic carbon and water [(g solute sorbed / g soil organic carbon) / (g solute / m^3 solution)] and f_{oc} is the soil organic carbon content (mg organic carbon / mg soil) (Domenico and Schwartz 1990).

The normalized soil adsorption coefficient (K_{oc}) can be determined from the following equation:

$$\log K_{oc} = 0.909 \log K_{ow} + 0.088 \qquad (4)$$

where K_{ow} is a dimensionless partition coefficient of an organic chemical between octanol (an organic liquid) and water; also known as the octanol/water partition coefficient (Hassett et al. 1983).

In order to determine the retardation factors and velocities for TCE and PCE with respect to the groundwater system at the Newmark site using the equations described above, the following parameters were identified:

- The organic carbon content for the soil medium located below the water table ($\geq$ 50 feet below the ground surface) is less than 0.1% in the San Bernardino area (Best 1992; Mackay and Vogel 1985; and Karickhoff 1981). Therefore, a value of 0.1% will be used for a conservative estimate of the retardation factor.

- The log K_{ow} values for TCE and PCE are 2.29 and 2.60 respectively (Vershueren 1983).

- The porosity of the soil medium at the Newmark site is assumed to be 30% (Domenico and Schwartz 1990).

- The soil particle density for all soil types is approximately 2.65 g/cm^3 (Domenico and Schwartz 1990).

The estimated retardation factors and velocities of TCE and PCE in the groundwater are listed in Table 28. The estimated velocity of PCE in the groundwater will be used to estimate remediation times for the Newmark plume. The estimated remediation times, under several extraction scenario conditions, will be described in the next section.

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Table 28

ESTIMATED RETARDATION FACTORS (R_f) AND VELOCITIES OF TCE AND PCE IN THE GROUNDWATER

Average Groundwater Velocity (ft/yr)	TCE R_f	PCE R_f	Average TCE Velocity (ft/yr)	Average PCE Velocity (ft/yr)
355.9	1.91	2.75	186.3	129.4

14.0 ESTIMATED REMEDIATION TIMES FOR THE NEWMARK PLUME

In this section, remediation times, under both best-case and worst-case conditions for the Newmark plume, will be estimated for extraction scenarios no. 6, 7 and 8. For estimating the remediation time under best-case conditions, it will be assumed that TCE and PCE travel at the same velocity as the groundwater. The following equation will be used for this estimation:

$$R_b = D / V_w (5)$$

where R_b is the remediation time under best-case conditions (yr); D is the centerline distance along the Newmark plume from the Newmark wellfield to the location of the extraction wells (ft); and V_w is the average velocity of the groundwater (ft/yr).

For estimating the remediation time under worst-case conditions, it will be assumed that TCE and PCE travel at a retarded velocity relative to the groundwater. The following equation will be used for this estimation:

$$R_w = D / V_{PCE} \qquad (5)$$

where R_w is the remediation time under worst-case conditions (yr); D is the centerline distance along the Newmark plume from the Newmark wellfield to the location of the extraction wells (ft); and V_{PCE} is the average velocity of PCE in the groundwater (ft/yr).

14.1 Estimated Remediation Times For Extraction Scenario No. 6

Remediation times, under best-case and worst-case conditions, have been estimated for extraction scenario no. 6. Two extraction regions were used in extraction scenario no. 6: Newmark wellfield and the downgradient edge of the Newmark plume. Therefore, the centerline distance was measured from the Newmark wellfield to the downgradient edge of the Newmark plume. Table 29 lists the remediation times estimated for extraction scenario no. 6.

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Table 29

ESTIMATED REMEDIATION TIMES FOR EXTRACTION SCENARIO NO. 6

Centerline Distance (ft)	Average Velocity (ft/yr)		Remediation Time (yrs)	
	Groundwater	PCE	Best-case[a]	Worst-case[b]
Newmark wellfield to edge of Newmark plume = 21,650	355.9	129.4	60.8	167.3

[a] Remediation time is calculated using the average velocity of the groundwater.
[b] Remediation time is calculated using the average velocity of PCE in the groundwater.

14.2 Estimated Remediation Times For Extraction Scenario No. 7

Remediation times, under best-case and worst-case conditions, have been estimated for extraction scenario no. 7. Two extraction regions were used in extraction scenario no. 7: Newmark wellfield, the middle area and the downgradient edge of the Newmark plume. Therefore, the centerline distance was measured from the Newmark wellfield to the middle area of the Newmark plume and from the middle area to the downgradient edge of the Newmark plume. Table 30 lists the remediation times estimated for extraction scenario no. 7.

14.3 Estimated Remediation Times For Extraction Scenario No. 8

Remediation times, under best-case and worst-case conditions, have been estimated for extraction scenario no. 8. Two extraction regions were used in extraction scenario no. 8: Newmark wellfield and along the centerline of the lower portion of the Newmark plume. Therefore, the centerline distance was measured from the Newmark wellfield to the downgradient edge of the Newmark plume. Table 31 lists the remediation times estimated for extraction scenario no. 8.

15.0 RESULTS AND LIMITATIONS

15.1 Results of the Extraction Scenarios and Remediation Times

The project flow model was used to determine an efficient and feasible remediation extraction system for the Newmark plume.

Nine extraction scenarios were simulated, one of which was a "no action" scenario. The extraction scenarios were composed of extraction wells located in one or any combination of four extraction regions of the Newmark plume, with exception to extraction scenario no. 9. Extraction scenario no. 9 was simulated without using any additional extraction areas, other than the existing water-supply wells. The extraction regions of the Newmark plume are:

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Table 30

ESTIMATED REMEDIATION TIMES FOR EXTRACTION SCENARIO NO. 7

Centerline Distance (ft)	Average Velocity (ft/yr)		Remediation Time (yrs)	
	Groundwater	PCE	Best-case[a]	Worst-case[b]
Newmark wellfield to middle of Newmark plume = 8300	355.9	129.4	23.3	64.1
Middle to edge of Newmark plume = 13,350	355.9	129.4	37.5	103.2

[a] Remediation time is calculated using the average velocity of the groundwater.
[b] Remediation time is calculated using the average velocity of PCE in the groundwater.

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Table 31

ESTIMATED REMEDIATION TIMES FOR EXTRACTION SCENARIO NO. 8

Centerline Distance (ft)	Average Velocity (ft/yr)		Remediation Time (yrs)	
	Groundwater	PCE	Best-case[a]	Worst-case[b]
Newmark wellfield to edge of Newmark plume = 21,650	355.9	129.4	60.8	167.3

[a] Remediation time is calculated using the average velocity of the groundwater.
[b] Remediation time is calculated using the average velocity of PCE in the groundwater.

- Downgradient edge of the Newmark plume;
- Middle of the Newmark plume (adjacent to the eastern edge of Shandin Hills);
- Newmark wellfield; and
- Centerline of the southern half of the Newmark plume.

Extraction scenarios no. 1 through 4 were simulated for a short-time span of five years and were simulated for each of the four extraction regions. The first four extraction scenarios were preliminary scenarios simulated for the purpose of quickly estimating of the number of extraction areas (with their locations and pumping rates) that is required to capture the Newmark plume at each of the four extraction regions of the Newmark plume.

Extraction scenarios no. 5 through 8 were simulated for 35 years using combinations of the extraction area locations for the four extraction regions. Extraction scenarios no. 5 through 8 were final scenarios simulated for the purpose of determining an efficient and feasible extraction system for remediating the Newmark plume.

Extraction scenario no. 9 was simulated for 35 years using just the existing water-supply wells. This extraction scenario is also known as the "no action" scenario. Extraction scenario no. 9 was simulated for the main purpose of estimating the time required to remediate the Newmark plume.

Extraction scenarios no. 6 through 9 will be summarized in this section. Extraction scenarios no. 1 through 4 will not be summarized in this section since they were only preliminary simulations to extraction scenarios no. 5 through 8. Since extraction areas located in the Newmark wellfield are considered a vital part of the remediation extraction system, extraction scenario no. 5 is not seriously being considered as an efficient and feasible remediation extraction system and, therefore, will not be summarized in this section.

15.2 Velocities of the Groundwater and TCE and PCE in the Groundwater

Extraction scenario no. 9 ("no action" scenario) was simulated for 35 years without using any additional extraction areas, other than the existing water-supply wells. This scenario was used to calculate an average groundwater velocity that could be used in the estimation of remediation times for the Newmark plume.

For the first step in the calculation of the remediation times, groundwater velocities were calculated for three areas of the Newmark plume and then averaged together. The average groundwater velocity equaled 355.9 ft/yr, which appears to be the best estimate available using the existing information.

For the second step in the calculation of the remediation times, retardation factors in relation to the Newmark plume area, were estimated for TCE and PCE in the groundwater system. The estimated retardation factors for TCE and PCE were 1.91 and 2.75, respectively. The average groundwater velocity divided by the TCE and PCE retardation factors yielded average TCE and PCE velocities in the groundwater of 186.3 and 129.4 ft/yr, respectively.

Since PCE travels at a slower velocity than TCE, the retarded velocity for PCE was used for estimating the remediation times under worst-case conditions. The average groundwater velocity was used for estimating the remediation times under best-case conditions.

15.3 Extraction Scenario No. 6

Extraction scenario no. 6 consisted of three extraction areas located at the downgradient edge of the Newmark plume and five extraction areas located in the Newmark wellfield, four of which were the existing Newmark wells. Extraction scenario no. 6 was simulated for 35 years.

The extraction areas for the Newmark wellfield successively captured the imaginary particles placed upgradient of the Newmark wellfield. Also, some imaginary particles placed downgradient of the Newmark wellfield were captured by the extraction areas. The pumping rate for the added extraction area was 800 gpm throughout the entire 35-year simulation. Normal pumping rates for the time period between

January 1986 through December 1990 were used for the Newmark wells throughout the entire 35-year simulation.

The three extraction areas, located at the downgradient edge of the Newmark plume, successively captured all imaginary particles that reached the downgradient edge of the Newmark plume. Four of the imaginary particles, that remained upgradient of the downgradient edge of the Newmark plume, were migrating downgradient within the capture zone of the downgradient extraction areas. The total pumping rate for the three downgradient extraction areas equaled 7000 gpm throughout the entire 35-year simulation.

Remediation times were estimated for the Newmark plume area extending from the Newmark wellfield to the downgradient edge of the Newmark plume. Remediation times were estimated under best-case conditions and worst-case conditions. Best-case conditions are described as TCE and PCE traveling at the same velocity of the groundwater and worst-case conditions are described as TCE and PCE traveling at a retarded velocity. Table 32 summarizes the estimated remediation times for best-case and worst-case conditions and the number, street locations and pumping rates of the extraction areas for extraction scenario no. 6.

15.4 Extraction Scenario No. 7

Extraction scenario no. 7 consisted of three extraction areas located at the downgradient edge of the Newmark plume, five extraction areas located in the Newmark wellfield (four of which were the existing Nemwark wells), and two extraction areas located adjacent to the northeast edge of Shandin Hills (middle area of Newmark plume). Extraction scenario no. 7 was simulated for 35 years. Extraction areas placed at the three regions of the Newmark plume successively captured all imaginary particles placed along the outside perimeter of the Newmark plume.

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Table 32

SUMMARY OF EXTRACTION SCENARIO NO. 6

Extraction Area	Approximate Location	Pumping Rate (gpm)	Remediation Time (yrs)	
			Best-case[a]	Worst-case[b]
Downgradient Edge of Newmark Plume				
8	on Arrowhead Ave.; 150' S/of 14th St.	2000		
9	200' E/of Mt. View Ave.; 300' N/of Wabash St.	2000		
10	250' E/of Sierra Way; on 14th St.	3000		
Newmark wellfield of Newmark Plume				
Newmark 1[c]	NE corner of "A" St. & Western Ave.	0 to 2910[d]	Remediation from Newmark wellfield to edge of Newmark plume	
Newmark 2[c]	175' s/of Reservoir Dr.; 40' W/of Magnolia Dr.			
Newmark 3[c]	95' N/of 42nd St.; 280' E/of Western Ave.			
Newmark 4[c]	65' S/of Reservoir Dr.; 50' E/of Western Ave.	0 to 1585[e]		
5	450' W/of 4th St.; 500' S/of 42nd St.	800	60.8	167.3

[a] Remediation time is calculated using the average velocity of the groundwater.
[b] Remediation time is calculated using the average velocity of PCE in the groundwater.
[c] Existing water-supply well.
[d] Total pumping rate range for Newmark 1,2 & 3 for 1986 through 1990 was used in the 35-year simulation.
[e] Pumping rate range for Newmark 4 for 1986 through 1990 was used in the 35-year simulation.

The extraction areas for the Newmark wellfield captured the imaginary particles placed upgradient and some of the imaginary particles placed downgradient of the Newmark wellfield. The pumping rate for the added extraction area was 800 gpm throughout the entire 35-year simulation. Normal pumping rates for the time period between January 1986 through December 1990 were used for the Newmark wells throughout the entire 35-year simulation.

The two extraction areas adjacent to the northeast edge of Shandin Hills captured the upgradient imaginary particles that were not captured by the extraction areas at the Newmark wellfield. The total pumping rate for the two middle extraction areas equaled 4000 gpm throughout the entire 35-year simulation.

The three extraction areas, located at the downgradient edge of the Newmark plume, successfully captured all imaginary particles that reached the downgradient edge of the Newmark plume. The total pumping rate for the three downgradient extraction areas equaled 7000 gpm throughout the entire 35-year simulation.

Best-case and worst-case remediation times were estimated for the Newmark plume area extending from the Newmark wellfield to the middle area of the Newmark plume. Also, best-case and worst-case remediation times were estimated for the Newmark plume area extending from the middle area to the downgradient edge of the Newmark plume. Table 33 summarizes the estimated remediation times for best-case and worst-case conditions and the number, street locations and pumping rates for the extraction areas for extraction scenario no. 7.

15.5 Extraction Scenario No. 8

Extraction scenario no. 8 consisted of three extraction areas located along the centerline of the lower end of the Newmark plume and five extraction areas located in the Newmark wellfield, four of which were the existing Newmark wells. Extraction scenario no. 8 was simulated for 35 years.

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Table 33

SUMMARY OF EXTRACTION SCENARIO NO. 7

Extraction Area	Approximate Location	Pumping Rate (gpm)	Remediation Time (yrs)	
			Best-case[a]	Worst-case[b]
Downgradient Edge of Newmark Plume				
8	on Arrowhead Ave.; 150' S/of 14th St.	2000		
9	200' E/of Mt. View Ave.; 300' N/of Wabash St.	2000		
10	250' E/of Sierra Way; on 14th St.	3000		
Newmark wellfield of Newmark Plume				
Newmark 1[c]	NE corner of "A" St. & Western Ave.	0 to 2910[d]	Remediation from Newmark wellfield to middle of Newmark plume	
Newmark 2[c]	175' s/of Reservoir Dr.; 40' W/of Magnolia Dr.			
Newmark 3[c]	95' N/of 42nd St.; 280' E/of Western Ave.			
Newmark 4[c]	65' S/of Reservoir Dr.; 50' E/of Western Ave.	0 to 1585[e]		
5	450' W/of 4th St.; 500' S/of 42nd St.		23.3	64.1
Middle Area of Newmark Plume				
14	150' E/of Sierra Way; 200' N/of Ralston Ave.	2000	Remediation from middle to edge of Newmark plume	
15	100' E/of Mt. View Ave.; 200' S/of 39th St.	2000	37.5	103.2

[a] Remediation time is calculated using the average velocity of the groundwater.
[b] Remediation time is calculated using the average velocity of PCE in the groundwater.
[c] Existing water-supply well.
[d] Total pumping rate range for Newmark 1,2 & 3 for 1986 through 1990 was used in the 35-year simulation.
[e] Pumping rate range for Newmark 4 for 1986 through 1990 was used in the 35-year simulation.

The extraction areas for the Newmark wellfield successively captured the imaginary particles placed upgradient and some of the imaginary particles placed downgradient of the Newmark wellfield. The pumping rate for the added extraction area was 800 gpm throughout the entire 35-year simulation. Normal pumping rates for the time period between January 1986 through December 1990 were used for the Newmark wells throughout the entire 35-year simulation.

The three extraction areas, located along the centerline, captured the upgradient imaginary particles that migrated and reached the centerline extraction areas. One of the imaginary particles, which had originated north of Shandin Hills, migrated around the east edge of Shandin Hills and stopped next to Shandin Hills. This imaginary particle was not captured by existing water-supply wells. Several imaginary particles upgradient of the centerline extraction areas were captured by existing water-supply wells.

Seven of the imaginary particles, placed on the southeastern downgradient edge of the Newmark plume and downgradient of the centerline extraction areas, were not pulled towards and captured by the centerline extraction areas. These seven imaginary particles migrated towards the south/southeast. One of these seven imaginary particles migrated southeast and out of the model area. The other six imaginary particles were captured by existing water-supply wells: 17th Street well, 16th Street well, 7th Street well and Gilbert Street well.

Best-case and worst-case remediation times were estimated for the Newmark plume area extending from the Newmark wellfield to the downgradient edge of the Newmark plume. Table 34 summarizes the estimated remediation times for best-case and worst-case conditions and the number, street locations and pumping rates of the extraction areas for extraction area no. 8.

15.6 Limitations

It is always important to remember that groundwater flow models and other associated computer software are only tools used to interpret past, present and future groundwater flow conditions. Therefore, one needs to be aware of the limitations existing in the model software and project flow model that may have resulted in inaccuracies in the extraction scenario simulations. They are:

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Table 34

SUMMARY OF EXTRACTION SCENARIO NO. 8

Extraction Area	Approximate Location	Pumping Rate (gpm)	Remediation Time (yrs)	
			Best-case[a]	Worst-case[b]
Centerline of Newmark Plume				
16	100' E/of Mt. View Ave.; 250' N/of 18th St.	4000		
17	100' E/of Mt. View Ave.; 200' N/of Highland Ave.	3000		
18	on Mt. View Ave.; 150' N/of 27th St.	3000		
Newmark wellfield of Newmark Plume				
Newmark 1[c]	NE corner of "A" St. & Western Ave.	0 to 2910[d]	Remediation from Newmark wellfield to edge of Newmark plume	
Newmark 2[c]	175' s/of Reservoir Dr.; 40' W/of Magnolia Dr.			
Newmark 3[c]	95' N/of 42nd St.; 280' E/of Western Ave.			
Newmark 4[c]	65' S/of Reservoir Dr.; 50' E/of Western Ave.	0 to 1585[e]		
5	450' W/of 4th St.; 500' S/of 42nd St.	800	60.8	167.3

[a] Remediation time is calculated using the average velocity of the groundwater.
[b] Remediation time is calculated using the average velocity of PCE in the groundwater.
[c] Existing water-supply well.
[d] Total pumping rate range for Newmark 1,2 & 3 for 1986 through 1990 was used in the 35-year simulation.
[e] Pumping rate range for Newmark 4 for 1986 through 1990 was used in the 35-year simulation.

- Difficulties in the project flow model calibration due to lack of aquifer description data;

- Scaling effects in the project flow model;

- Grid spacing and model layer resolution for placing extraction areas; and

- Gridding and plotting resolution of SURFER and PATH3D.

The first set of limitations are due to lack of aquifer description data, which have created difficulties in the project flow model calibration. Aquifer description data (for example, hydraulic conductivities, streamflow values, elevations of model layers, and the distribution of heads within the aquifer) are seldom known accurately or completely, thus producing data error. This can create difficulties in accurately calibrating the project flow model. For example, streamflow values have been used as calibration data for the project flow model. Estimates of flux measurements usually have large errors associated with the field measurements. Nevertheless, it is advisable to use estimates of flow as calibration values, in addition to heads, for achieving a unique calibration (Anderson and Woessner, 1992).

Furthermore, calibration is difficult because values for aquifer parameters and hydrologic stresses are typically known at only a few nodes and, even then, estimates are influenced by uncertainty. Calibration values ideally should coincide with nodes, but in practice this will seldom be possible. This introduces interpolation errors caused by estimating calibration values for grid cells.

Lack of aquifer data contributed particularly to dry cell and boundary condition problems in the calibration of the project flow model. These dry cell and boundary condition problems were avoided and minimized when possible. The dry cell and boundary condition problems that occurred during the calibration of the project flow model are described below:

- Several dry cells persisted throughout the calibration process. Dry cells (30,15,1), (30,16,1), (31,16,1), (32,16,1), (33,17,1), (34,17,1), (31,16,2) and (32,16,2) are located adjacent to the San Andreas fault, just north of the northeastern edge of Shandin Hills. These dry cells remained dry throughout the calibration of the transient-state model and simulations of the extraction scenarios. These dry cells were difficult to remedy due to the combination of boundary effects between San Andreas fault and northeastern edge of Shandin Hills and the groundwater gradient and flow direction in this same area.

Dry cells (24,21,1), (24,21,2), and (25,22,1) are located southeast of the Newmark wells, adjacent to Shandin Hills. These dry cells became dry only during the simulation of the extraction scenarios. Cells (24,21,1) and (24,21,2) went dry when extraction areas were added to the Newmark plume area, due to boundary effects of Shandin Hills and groundwater gradient and flow direction in this same area. When extraction areas at the Newmark wellfield were pumped at higher rates, cell (25,22,1) went dry.

Dry cells (27,27,1) and (27,27,2) are located adjacent to the southeast edge of Shandin Hills. These dry cells became dry only during the simulation of extraction scenario no. 3. When extraction areas were added to the middle area of the Newmark plume, these cells went dry due to boundary effects of the southeast edge of Shandin Hills and groundwater gradient and flow direction in this same area.

- The water elevations simulated for the area surrounding Shandin Hills are not very accurate due to the boundary effects of Shandin Hills as no-flow area. Shandin Hills tends to prohibit the flow of groundwater around the east side of Shandin Hills in conjunction with the San Andreas fault (which is also identified as a no-flow area to groundwater flow). The back-up of groundwater north of Shandin Hills is evident in the hydrographs for Newmark #3 well (Figure 25 in Appendix K). The simulated water elevations for Newmark #3 well mimic the actual trend of the observed water elevations, but still remain an average of 40 feet above the observed water elevations.

- The water elevations simulated for the middle area of the Newmark plume between East Twin Creek and Shandin Hills followed the same trend as the observed water elevations in this area. However, the simulated water elevations tended to be higher than the observed water elevations in this area.

  This is evident in the hydrographs for Waterman Avenue well (Figure 25 in Appendix K) and 31st Street and Mountain View well (Figure 26 in Appendix K). For both of these hydrographs, the simulated water elevations followed the trend of the observed water elevations, but with not as much rise and fall. The simulated water elevations ranged from 20 to 80 feet above the observed water elevations. This seems to be due to two model limitations: the model lacking capability of simulating the fluctuating recharge/discharge conditions of East Twin Creek on a very short-term basis and the boundary effects of the east side of Shandin Hills. It appears that the groundwater was not conveyed downgradient fast enough because it was held between East Twin Creek and Shandin Hills.

- It has been difficult to calibrate the water elevations in the northern area (north and east of Shandin Hills). This could be due to two reasons. First, this problem could be due to the lack of data on bedrock elevations in this area. Since the alluvium is thin in this area and the aquifer is unconfined, the water elevations, to some degree, probably follow the slope of the bedrock. However, very few data points of bedrock elevations are known throughout the entire model area and, therefore, this could cause mismatches between simulated and observed water elevations in the area north and east of Shandin Hills.

  Lack of water elevation data could be the second possibility that contributed to calibration difficulties in the northern area. Also, the field measurements available for the water elevations and the pumping rates have not all been measured on the same days of the month. This could cause some of the minor discrepancies between the simulated and observed water elevations evident in the hydrographs.

The second set of limitations is the error produced in the simulation from scaling effects in the project flow model. For example, heads may be measured in wells with long screens but the model may require point values. Head measurements averaged over long screens may be appropriate for calibrating a two-dimensional areal model but are usually not representative of heads calculated by a three-dimensional model.

Also, another scaling effect discussed by Gelhar (1986) can cause errors in simulated heads. The cells of the grid represent average aquifer properties within the cell. Field-measured heads, however, may be influenced by small-scale heterogeneities that are not captured by the model. Unmodeled heterogeneity causes error in the simulated heads.

The third set of limitations is the grid spacing and model layer resolution, which eventually poses problems in placing extraction wells. First, the grid spacing for the project flow model is 820 feet in the x-direction and 820 feet in the y-direction. When pumping of extraction areas are assigned to a grid cell, they are placed at the center of the grid cell. Therefore, no extraction area cannot be placed any closer to one another than 820 feet. To make up for the distance between extraction areas, where modeled particles can migrate through, the pumping rates have to be increased to capture the particles. When in reality, extraction areas could be placed closer together and pumped at slower rates.

Second, MODFLOW allows for the simulation of individual model layers, but does not allow for separate screening intervals within the model areas. Therefore, when placing the extraction areas, they could only be screened throughout the model layer and in separate intervals within the model layers. Therefore, when simulating the extraction scenarios, more groundwater is extracted from one extraction area than may be feasible for that extraction area in the field.

The fourth set of limitations is the gridding and plotting resolution of SURFER and PATH3D that may cause difficulties in interpreting water elevation contours. SURFER only allows for gridding and plotting of water elevation contours to the mid points of the grid cells located next to no-flow areas. However, PATH3D allows for plotting of the imaginary particle pathlines to any area of the grid cells located next to the no-flow areas. This creates difficulties in interpreting water elevation contours in the no-flow areas.

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